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We apply the FFST method to determine the crustal and mantle velocity structure beneath eastern Eurasia. Taking advantage of the broadband feature of seismic records, we measure P-wave (primary wave) relative delay times by waveform cross-correlation in three frequency bands (0.03–0.1 Hz, 0.1–0.5 Hz, and 0.5–2.0 Hz). The measurements are inverted jointly to constrain velocity heterogeneities with different distances from the central geometric rays. The effect of strong variations in crustal structure beneath this region on travel time data is removed by conducting a frequency-dependent crustal correction. A comprehensive data set, including waveforms from the publicly accessible sources and other seismic networks in the region, has been collected for this study. Our preliminary model has similar patterns of high- and low- velocity but higher magnitude anomalies than ray-based tomographic models. The resolution checkerboard tests suggest that the resolution is better beneath eastern China, reflecting the better sampling in that part of the model in the current data set. The procedures for computing frequency-dependent travel time corrections from the finite-frequency model have been developed and tested in relocating ground truth (GT) events.

This is the second year of a three-year effort to improve seismic calibration in eastern Eurasia. We will continue processing data to improve the 3-D FFST velocity model and construct an S-velocity model. The final model will be developed using joint body and surface waves, and wave propagation in the transition zone will be simulated. We will continue collecting waveforms and ground-truth (GT) data for model construction and validation.

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FINITE-FREQUENCY SEISMIC TOMOGRAPHY FOR EASTERN EURASIA

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Sponsored by Air Force Research Laboratory

Contract No. FA8718-05-C-0017[1,2]

ABSTRACT

Seismic calibration for nuclear explosion monitoring requires accurate, high-resolution 3-D velocity models. Although seismic event locations have been improved recently using more accurate travel times measured by waveform cross-correlation, ray-based models and predictions are not strictly self-consistent with travel times measured by waveform cross-correlation, which are sensitive to 3-D velocity perturbations around the geometric ray paths. Finite-frequency seismic tomography (FFST), which utilizes the 3-D sensitivity kernels to determine the structure that best fits the observations from waveform cross-correlation, provides a self-consistent approach in model development and event location.

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This is the second year of a three-year effort to improve seismic calibration in eastern Eurasia. We will continue processing data to improve the 3-D FFST velocity model and construct an S-velocity model. The final model will be developed using joint body and surface waves, and wave propagation in the transition zone will be simulated. We will continue collecting waveforms and ground-truth (GT) data for model construction and validation.

OBJECTIVES

Our main objectives are (1) to develop P and S velocity models beneath eastern Eurasia by conducting a joint body- and surface-wave tomography based on finite-frequency seismic waves, and (2) to carry out seismic calibration and validate the model and location improvement using GT data. Three-dimensional full waveform simulations will also be conducted to model wave propagation through the transition zone and seismic anisotropy.

RESEARCH ACCOMPLISHED

Data Processing

We collect and utilize a comprehensive data set to construct the new earth model beneath eastern Eurasia. Figure 1 shows the stations in the study region with broadband data. So far we have collected data from the Incorporated Research Institutions for Seismology (IRIS), Global Seismographic Network (GSN), Japanese F-net and JISNET, and Taiwan Broadband Seismic Network, as well as unique sources including permanent and portable seismic stations throughout the study area (e.g., part of the Chinese Digital Seismic Network). Other networks, including the International Monitoring System (IMS) and most of the Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) are being extracted and processed.

We process P-waves from global earthquakes in the updated Engdahl-van der Hilst-Buland (EHB) bulletins from 2001 to 2004 and the National Earthquake Information Center (NEIC) bulletins for more recent events with magnitude greater than 5.5 recorded by the seismic stations in eastern Eurasia. The broadband waveforms of the P-waves are filtered in high, intermediate, and low-frequency bands (0.5–2.0, 0.1–0.5, and 0.03–0.1 Hz, respectively) to help isolate the microseism and utilize the broad frequency range of the seismic records. We use an automated waveform cross-correction (VanDecar and Crosson, 1990) routine to measure the relative travel time delays of the arrivals in each frequency band for each event. The signal-to-noise ratio threshold is set to 20 for automated data selection in each frequency band, and each selected record is also examined manually for consistency. The signal-to-noise ratio is defined as the ratio of the peak-to-peak amplitude of the main arrival to the standard deviation of the time series in an 80-s window before the main arrival. Figure 2 shows the distribution of the events and phases in our data set.

The study region spans 20°S to 60°N and 60°E to 160°E. The tomographic model extends to 2500 km deep and is parameterized by a $128 \times 128 \times 64$ grid with spacing of 0.625°, 0.806°, and 39 km in latitude, longitude, and depth, respectively. Details of the FFST methodology used in this work are given in Hung et al. (2004) and Yang et al., (2005). The inversion of the massive matrix is approximated by the iterative solution of the LSQR algorithm (Paige et al., 1982). The norm damping factor of the inversion is determined by the trade-off analysis of model roughness versus variance reduction (Menke, 1989).

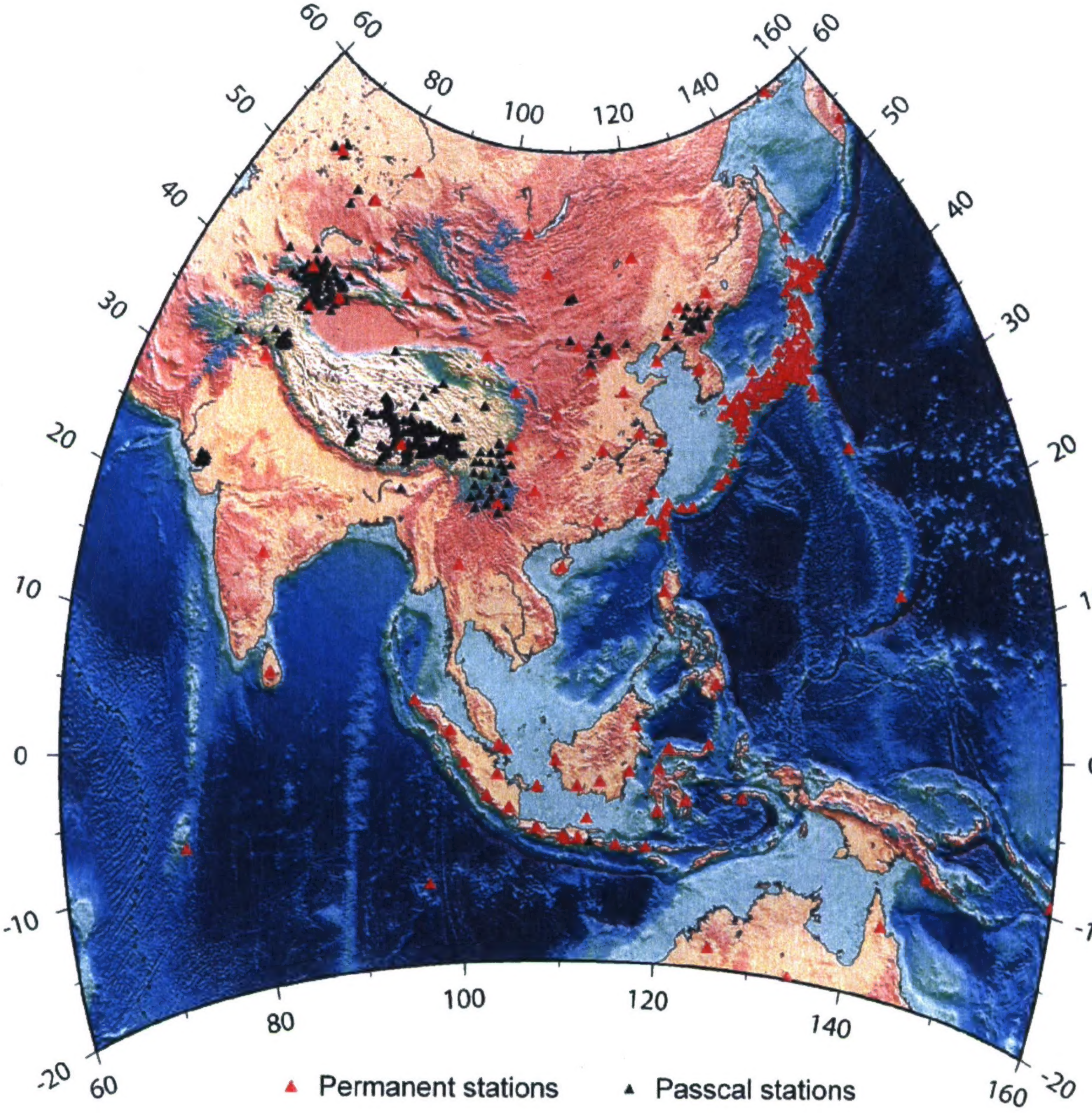

Figure 1. Triangles mark the locations of broadband seismic stations in Eastern Eurasia (red: Permanent stations; black: PASSCAL stations). Data from the PASSCAL stations will be included in our final model.

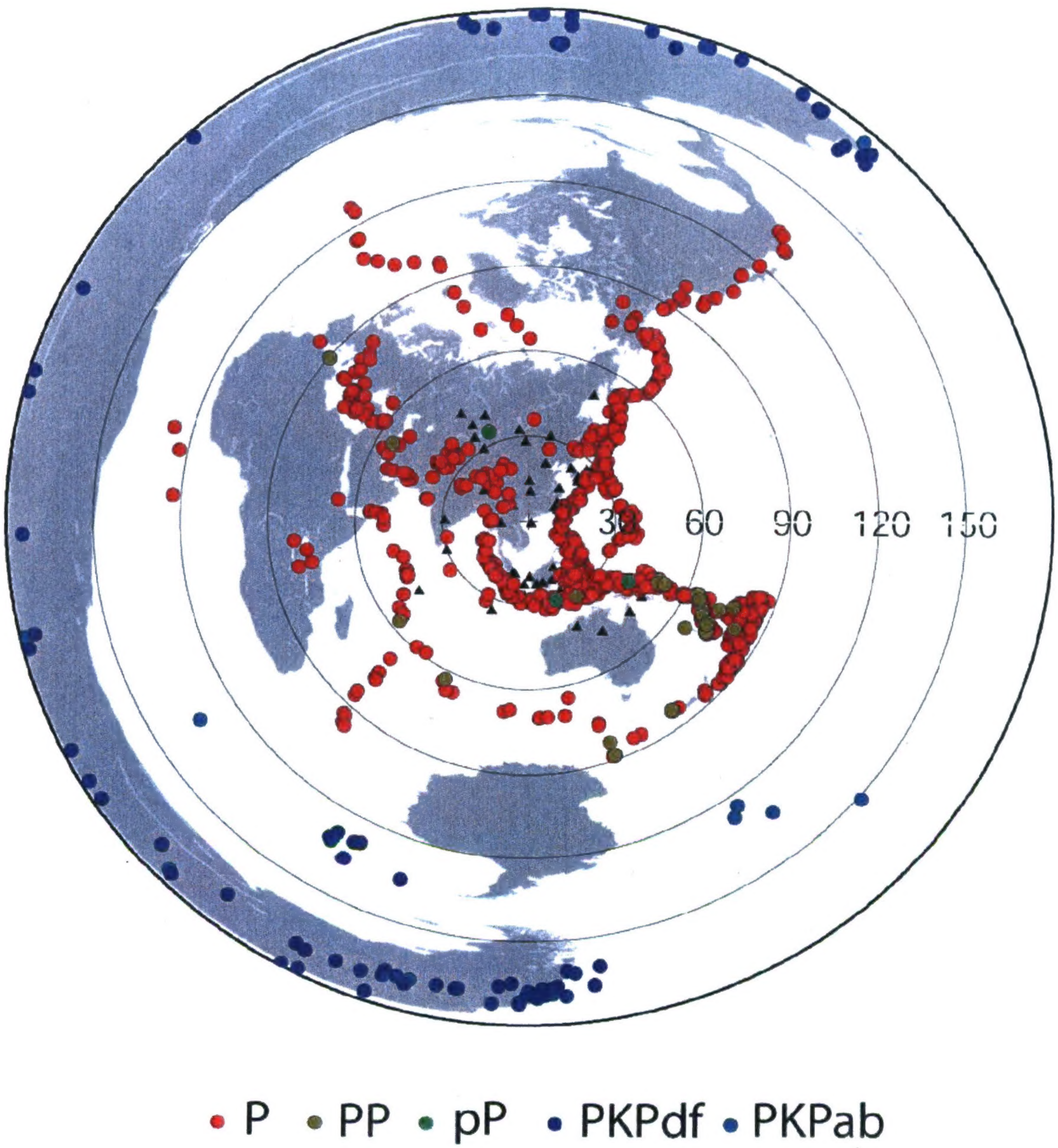

Figure 2. Locations of the earthquakes with useful phases (color circles) and stations (triangles) in the study region. The projection is centered at Hainan, China. Numbers mark the distance in degrees from the center of map projection.

Crustal Correction

Removing the crustal signature from teleseismic travel times is an important procedure to reduce the tradeoff between crustal and mantle velocity heterogeneities in seismic tomography. In regions having large variations like Eastern Eurasia, this is particularly important. Because reverberations of long- and short-period body wave arrivals in the crust affect the waveforms of the direct arrivals differently, the crustal effects on travel times measured by waveform cross-correlation are frequency dependent. With synthetic responses of selected crustal models we have shown (Figure 3) the importance of frequency-dependent crustal corrections to finite-frequency body-wave travel time tomography. The differences in crustal correction between long- and short-period body waves at the same station can be as large as 0.6 s, depending on the crustal thickness, velocity contrast at the Moho, and layering within the crust.

The frequency-dependent crustal correction can be approximated, to the first order, by cross-correlating the impulse responses of a crust model filtered in a narrow frequency band (Yang and Shen, 2006). We use a crustal model from Sun et al. (2005) for stations in China, and CRUST2.0 (crustal model) (Bassin et al., 2000) for stations elsewhere to calculate the travel time difference with respect to IASP91 for the three frequency bands, and apply those frequency dependent adjustments to teleseismic travel times.

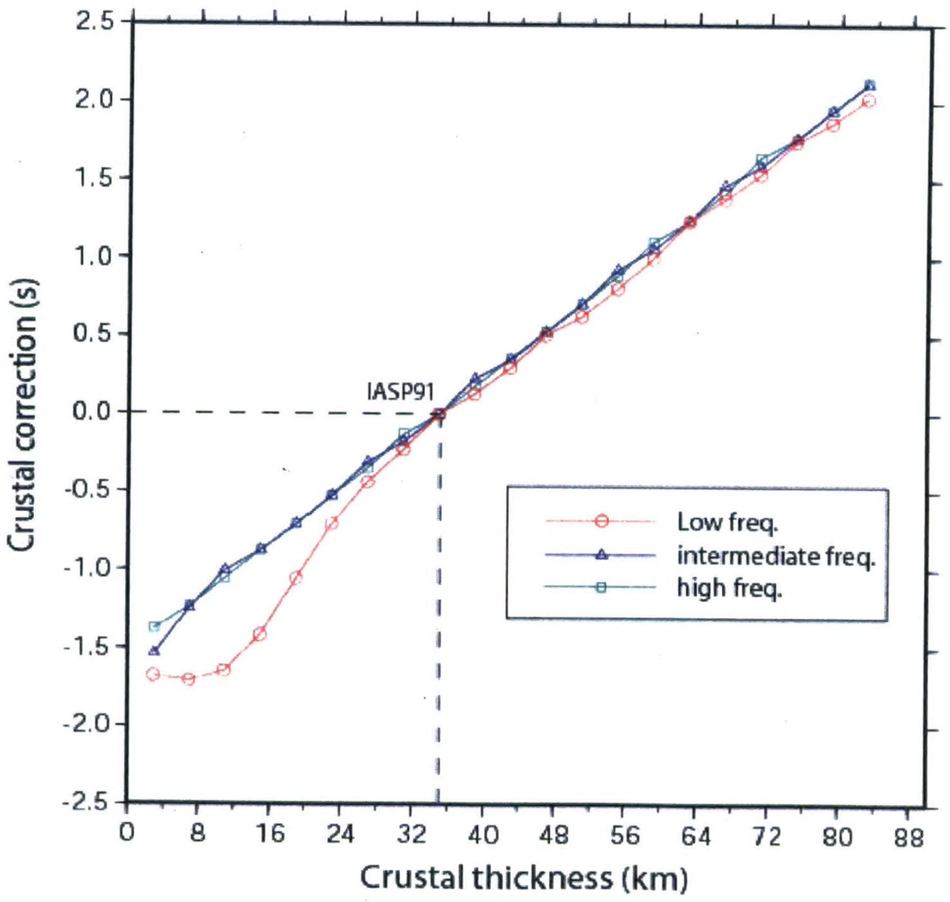

Figure 3. Effect of the crustal thickness on crustal corrections for the high- (0.5–2.0 Hz), intermediate- (0.1–0.5 Hz) and low- (0.03–0.1 Hz) frequency signals from a synthetic experiment. The crust is a two-layer model with the same Vp, Vs and density as those of IASP91. The thicknesses of the upper and lower crust are increased or decreased by the same amount in each calculation.

Preliminary Results

Figure 4 shows the sampling density from high, intermediate, and low frequency P-waves from teleseismic earthquakes in our data set. Because of the relatively narrow "banana-doughnut" sensitivity kernels of high-frequency P-waves, the sampling of high-frequency P-waves (Figure 4a) resembles that in ray theory. At intermediate and low frequencies, the broad sensitivity kernels provide a more smooth coverage of the structure. FFST combines the sensitivity kernels in all frequency bands in the inversion. There is a good data coverage in the depth range of 400–1500 km, but large gaps exist in the shallow upper mantle and crust due to the sparse station distribution. Other datasets (e.g., PASSCAL and IMS) and surface bouncing phases (pP, PP) will reduce the gaps.

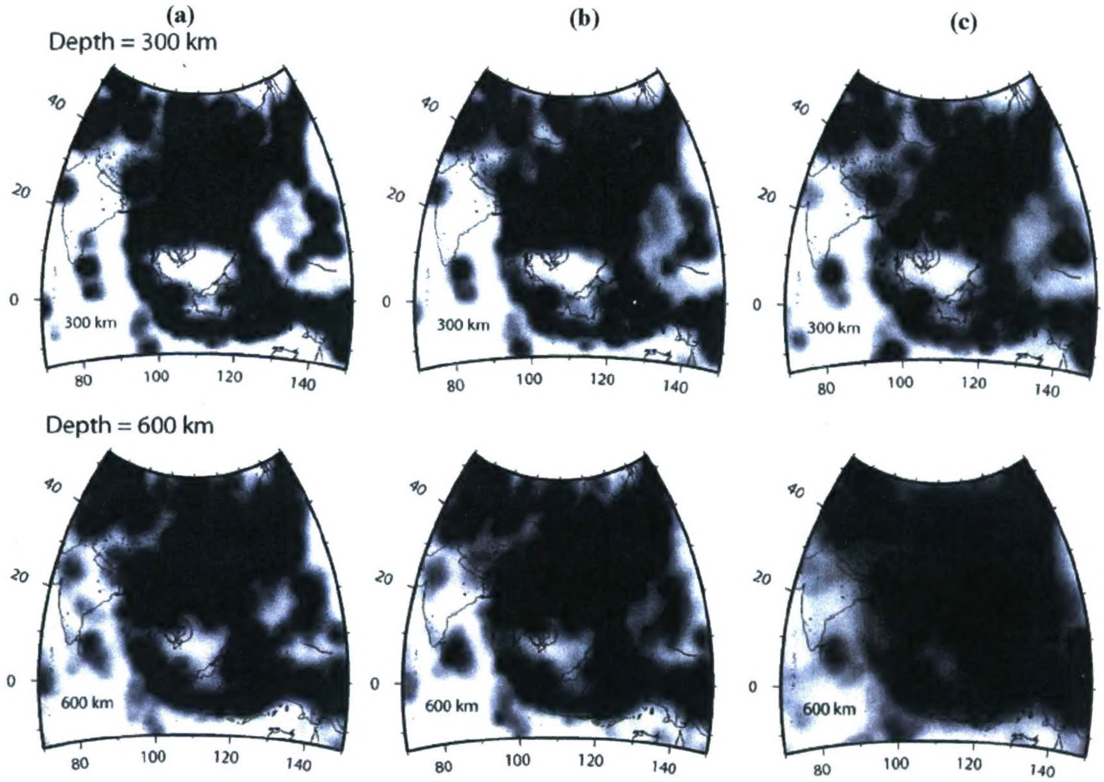

Figure 4. Sampling of the model space by 3-D sensitivity kernels of P-waves at (a) high (left column), (b) intermediate (middle column) and (c) low (right column) frequencies at 300 km (top row) and 600 km (bottom row) depth. Because of the broad sensitivity kernels, low-frequency arrivals reduce the gaps in the sampling of the higher frequency data.

Figure 5 shows the velocity anomalies at 225 and 525 km depth in our preliminary model. A comparison with the previous studies (e.g., Li et al., 2006) shows that our model has similar patterns of high and low velocity anomaly distribution but a higher magnitude than those ray-based tomographic models, indicating the 3-D sensitivity kernels are able to account for the wavefront healing effect of realistic seismic wave propagations. The resolution checkerboard tests suggest that the resolution is good beneath eastern China and along the Japanese island, reflecting the better data coverage and sampling in those regions. We will carry out the finite frequency surface wave tomography to provide higher resolution in the shallow structure and complement the body wave model.

So far we have established the process for model validation using GT event relocation. We developed the code for calculating relative travel time corrections from the kernels using the preliminary P-model. Travel time corrections were computed for IMS stations in Eurasia and applied to sample GT events for testing. We continue collecting GT data and will conduct event relocation to assess our new version of the 3-D velocity model.

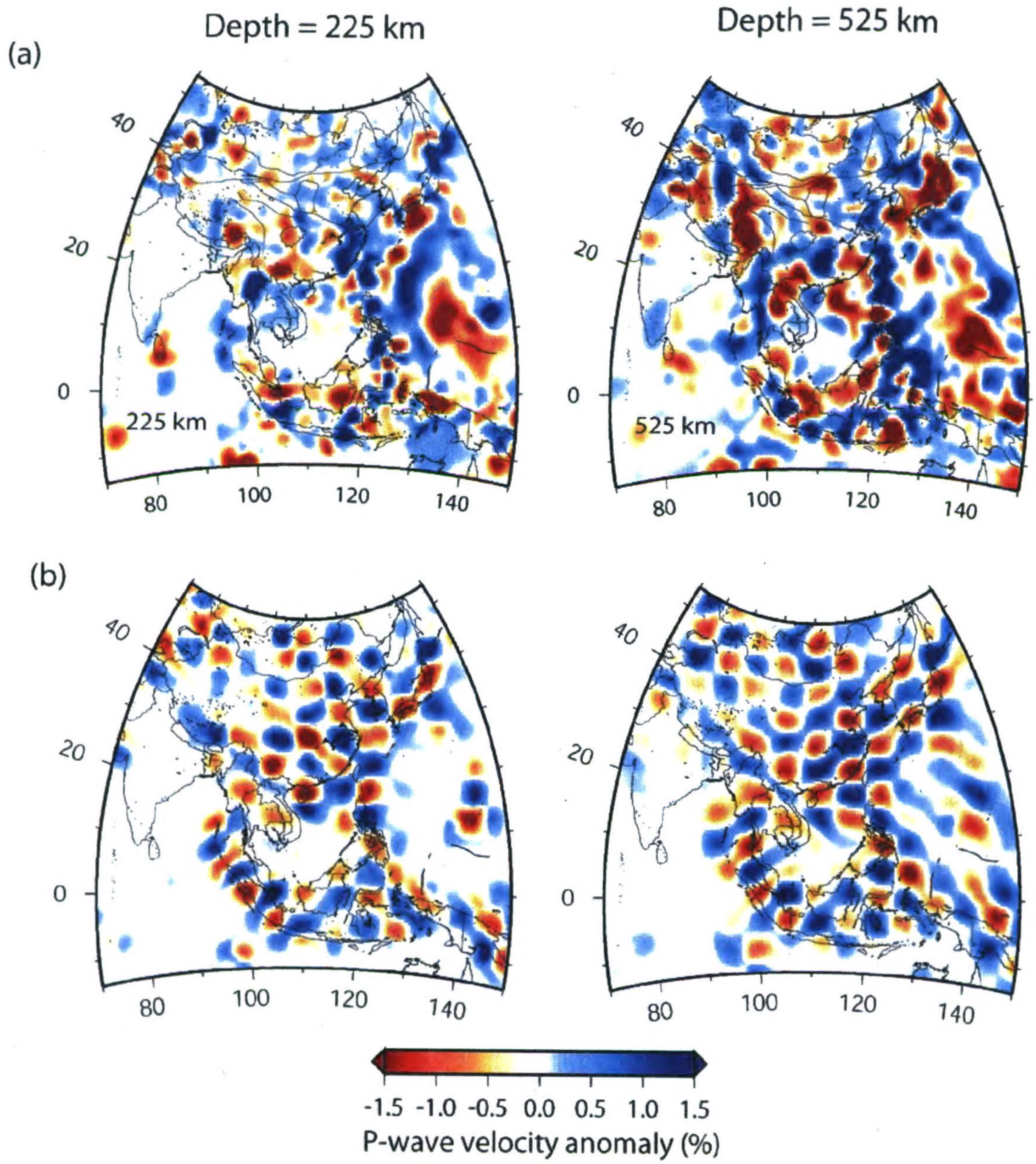

Figure 5. (a) Two horizontal slices of the tomographic model at 225 km and 525 km depth showing the velocity perturbation distribution in the mantle beneath Eastern Eurasia. (b) The checkerboard resolution tests. The structure beneath eastern China is better resolved due to a better sampling in the current dataset.

CONCLUSIONS AND RECOMENDATIONS

In this work we use a 3-D finite-frequency kernel-based approach to improve seismic calibration for nuclear explosion monitoring in eastern Eurasia. We collect and process a comprehensive data set using waveform cross-correlation to construct the FFST models. Preliminary tomographic inversions using finite-frequency kernels have demonstrated improvement in resolution compared to those based on ray theory. The initial model shows similar patterns compared to the previous studies using the ray-based approach but has higher magnitude anomalies. We will continue to process the remaining available earthquake waveforms and carry out the joint body and surface wave finite frequency tomography. The 3-D velocity models will be used in improving seismic calibration in Eurasia. The procedures for computing frequency-dependent travel time corrections from the finite-frequency model have been developed and tested in relocating GT events.

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